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Relativistic Thomson Scattering Experiment At BNL - Status Report

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Abstract

1.7×10^8 x-ray photons per 3.5 ps pulse have been produced in Thomson scattering by focusing CO_2 laser pulse on counter-propagating relativistic electron beam. We explore a possibility of further enhancement of process efficiency by propagating both beams in a plasma capillary.

Conventional synchrotron light sources based on using giga-electron-volt electron synchrotron accelerators and magnetic wigglers generate x-ray radiation for versatile application in multi-disciplinary research. An intense laser beam causes relativistic electron oscillations similar to a wiggler. However, because the laser wavelength is thousand times shorter than a wiggler period, very moderate electron energy is needed to produce hard x-rays via Thomson scattering. This allows using relatively compact mega-electron-volt linear accelerators instead of giga-electron-volt synchrotrons. Another important advantage of Thomson sources is a possibility to generate femtosecond x-ray pulses whereas conventional synchrotron sources have typically ~300 ps pulse duration. This promises to revolutionize x-ray research in chemistry, physics, and biology expanding it to ultra-fast processes. Thomson sources do not compete in repetition rate and average intensity with conventional light sources that operate at the megahertz frequency. However, Thomson sources have a potential to produce much higher photon numbers per pulse. This may allow developing a single shot exposure important for structural analysis of live biological objects.

The BNL Thomson source is a user's experiment conducted at the Accelerator Test Facility since 1998 by an international collaboration in High Energy Physics. Since inception, the ATF source produces the record peak x-ray yield, intensity and brightness among other similar proof-of-principle demonstrations attempted elsewhere (see Fig.1). Note that this result is achieved with a moderate laser power of 15 GW.

A key to this achievement is in choosing right apparatus and efficient interaction geometry. We use a CO_2 laser that delivers 10 times more photons per unit energy than the 1-μm laser, a high-brightness linac, and the most energy-efficient backscattering interaction geometry. The purpose of this report is to give an update on new results obtained during this year and our near-term plans.

Doing Thomson scattering experiment we brought into collision the 5 J, 180 ps CO_2 laser pulses with the 60 MeV, 3.5 ps e-beam using experimental setup shown schematically on Fig.2. Other relevant electron beam parameters are: bunch charge 0.5 nC, energy spread 0.15%, and normalized emittance ε_n=2 mm mrad. To make the exact 180^0 interaction, a parabolic copper mirror of the 15 cm focal length is placed on the way of the e-beam. Naturally, the mirror has a hole (5 mm in diameter) drilled along the e-beam axis to transmit both the electrons and the backscattered x-rays. Stepper motors provide two-axis tilt of the parabolic mirror for precision positioning of the laser focus on the e-beam. The mirror with a mounting assembly is shown in Fig.3.

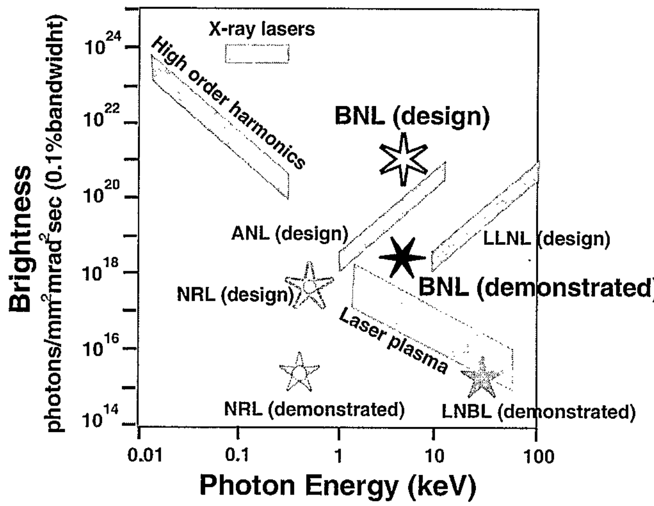


Figure 1. Survey of the US Thomson scattering experiments.

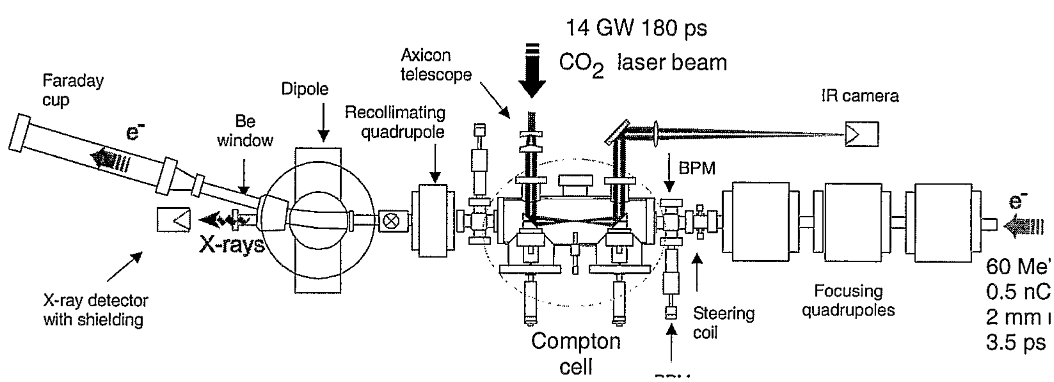


Figure 2. Principle diagram of the BNL Thomson scattering experiment.

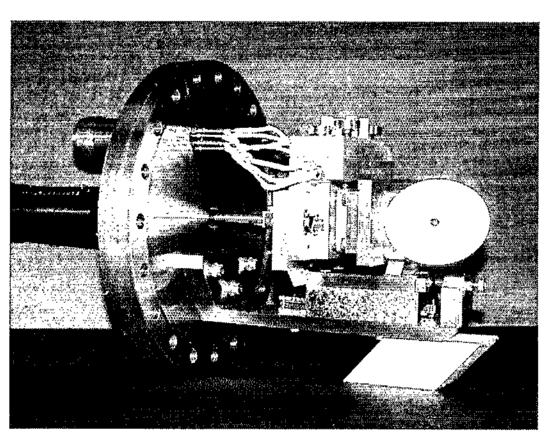


Figure 3. Parabolic mirror with a hole for e-beam and x-rays on a remotely controlled manipulator.

Fig. 4 shows simulated x-ray energy spectrum at the position of the detector. Feeding the experimental parameters of the electron beam and laser into the Monte-Carlo code CAIN we predict 340 million photons/pulse integrated over the entire 0-6.5 keV spectrum. Low-energy x-rays are attenuated on the Be window and in the air, and just 15% of the total generated photons are supposed to reach the Si detector (50 million photons/pulse). However, based on the detector calibration, we calculate that the observed signal accounts for 25 million photons/pulse in the 4-6.5 keV region. Correspondingly, we adopt two times smaller actual integral photon number. We consider that the discrepancy by a factor of two between the experiment and simulations could be due to imperfect alignment of the electron and laser beams. Since the x-ray pulse duration is equal to the electron bunch length (3.5 ps), peak photon density is estimated to be 5×10^{19} photons/second.

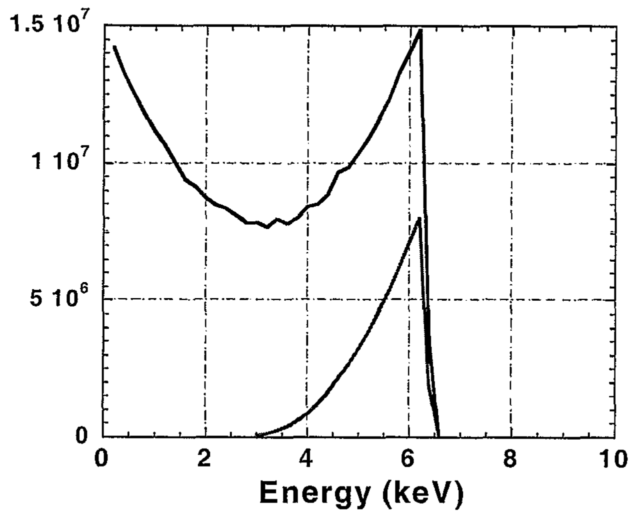


Figure 4: X-ray energy spectra simulated with CAIN. The upper curve shows the spectrum of all photons generated at the interaction point (3.4×10^8 photons/pulse), while the lower curve shows photons on the detector (5×10^7 photons/pulse).

Presently the ATF CO_2 laser pulse duration of 180 ps is limited by a narrow bandwidth of the laser preamplifier. Ongoing laser upgrade to the ~1 TW peak power includes installing a high-pressure broad-bandwidth preamplifier that allows shortening the pulse duration. Similarly we plan to upscale the e-beam parameters. The ATF linac delivers several picosecond, ~1 nC bunches. During the next year, a bunch compressor will be installed that will produce as short as 200 fs bunches. There are ideas to attempt even down to 20 fs bunch compression. The near-future plan includes opening femtosond x-ray beamline for ultra-fast user's experiments and study of nonlinear phenomena in relativistic Thomson scattering.

With a CO_2, laser electrons reach a relativistic quiver motion ($eE=mc\omega$) at the laser intensity of 10^{16} W/cm^2 to compare with 10^{18} W/cm^2 for the 1-μm laser. We will approach this intensity with the 1 TW CO_2 laser and expect strong harmonics observed above the fundamental 6.5 keV radiation [1].

Nonlinear Thomson scattering effect is certainly of a considerable fundamental interest. However, it is simultaneously a limitation on a way to increase spectral brightness of the Thomson source via the laser power increase. Indeed, if we look at the expression for the short-wavelength edge in Thomson scattering

$$\lambda_x = \frac{\lambda\left(1+a^2/2\right)}{4\gamma^2} \tag{1}$$

we see a dependence upon the laser strength parameter

$$a = eE/mc\,\omega = 0.85\times10^{-9}\lambda[\mu m]I^{1/2}\left[W/cm^2\right]. \tag{2}$$

This parameter varies in time and against transverse space coordinates in the laser beam. This results in considerable smearing of the integral x-ray spectrum. Finally, we arrive to a situation when the x-ray bandwidth becomes intensitydominated and a spectral brightness degrades. High laser energy and tight focusing of the laser pulse are both desirable to intensify Thomson scattering. What shall we do in order to get advantage of these but to stay below the relativistically strong laser intensity that compromises brightness? The only option is to use a long laser pulse. However, the laser pulse can not be stretched above the double Rayleigh distance, which is typically of the order of several picoseconds, without wasting the laser energy. To avoid this conflict, we propose to confine the laser-electron interaction region in the extended plasma channel [2]. This breaks a constraint on the laser pulse duration. This way we may use efficiently even nanosecond laser pulses and still produce femtosecond x-rays.

Choosing a plasma channel scheme for the Thomson source we apply certain selection rules. First, the channel wall shall not obscure the produced x-ray cone that has an opening angle of $1/\gamma$. Second, the plasma density needs to be much lower than 10^{19} cm^{-3} that is the critical density for the 10-μm radiation. These considerations point to the electric discharge scheme that allows controlling the plasma density [3]. By this method, the laser beam can be confined in the plasma core ~10 times smaller than the diameter of the discharge tube.

In a recent test conducted at BNL a two-section (ignition and main discharge) polypropylene capillary of the 1 mm inner diameter and 20 mm length was positioned in a vacuum chamber. Up to 14 kV pulsed voltage is applied to the capillary electrodes in the scheme shown in Fig.5.

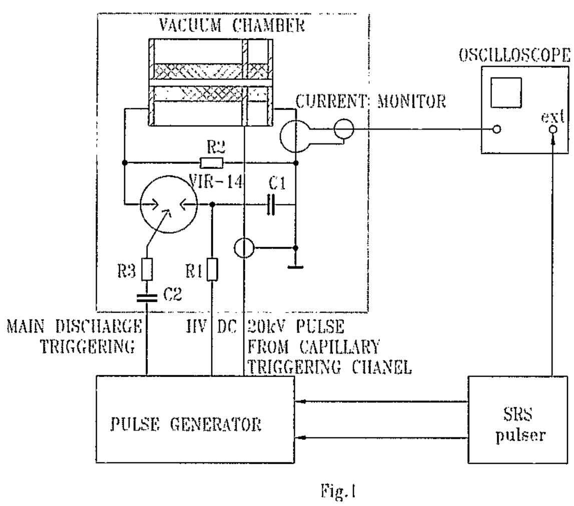
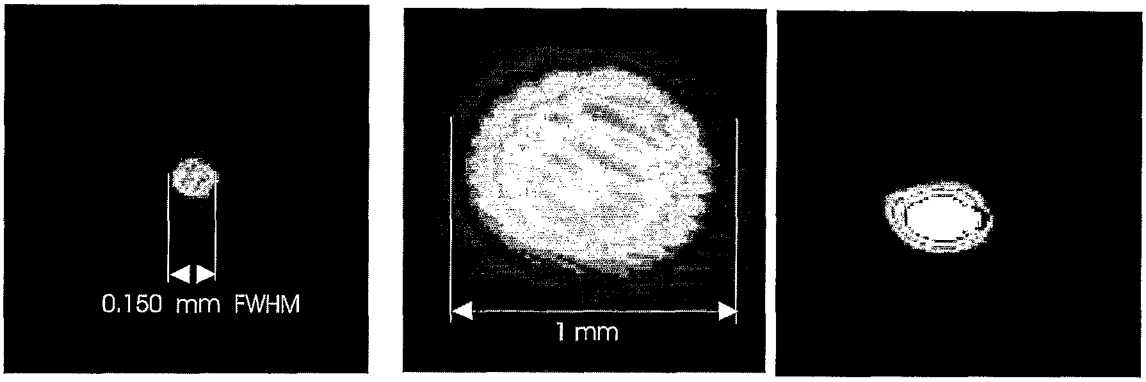


Figure 5: Electrical scheme of the capillary discharge experiment

The 200 ps, 100 mJ CO_2 laser pulse has been focused at the entrance of the capillary with a lens of the 20 cm focal length (F#=12). Another lens imaged the output laser beam with the ×7 magnification to the Electrophysics-5400 pyroelectric video-camera. Intensity profiles are grabbed with the Spiricon-4000 laser beam analyzer. Translation of the imaging lens allows observing cross-section of the laser beam at the focus or at the capillary exit plane.

Intensity distributions shown in Fig. 6a and 6b are obtained in the "free space" (capillary retracted). Image Fig. 6a taken at the focal point shows 160 μm (FWHM) spot size. Fig. 6b is taken at 20 mm distance downstream from the focus. Note that in order to stay within a linear response of the camera and the frame-grabber, images 6a and 6b are obtained with different attenuation. This permits measurement of the beam size that, as we see, expands approximately six times in diameter between the observation points that are spaced by ~$6Z_R$ (where Z_R is the Rayleigh distance)

When we insert a capillary with its entrance tip set at the focal point, establish proper discharge conditions (electrical current and timing) the observed intensity pattern changes from Fig.6b to Fig.6c without refocusing of the imaging lens. Comparison of the image at the plasma channel exit (Fig. 6c) with the distribution in free space at the equivalent distance from the focus (Fig. 6b) demonstrates an evident optical guiding effect.



a b c

Figure 6. CO_2 laser beam transmission through a plasma channel:
a) image of the laser beam at the focal point; b) laser beam 20 mm downstream from the focus in the free space (capillary retracted, attenuation adjusted); c) laser beam at the exit of the 20 mm long plasma discharge with the capillary entrance placed at the focal point (no attenuation adjustment between b) and c)).

The best channeling condition is obtained at the 12-14 kV voltage applied to the capillary, peak current ~400 A, and the laser pulse delayed by ~120 ns (3/4 of the current period) from the current peak.

The reported here result seems to be the first experimental verification of the 10 μm laser beam guiding in a plasma channel. Our observations, being of a special importance for CO_2 laser applications, provide a confirmation of establishing an optical channel in the plasma of the 10^{17}-$10^{18}cm^{-3}$ density range. These conditions are of the interest for such important application of guided laser beams as the laser wakefield acceleration.

We plan to conduct Thomson scattering experiment in a plasma channel in the very short future. The goal of this experiment will be demonstration of efficient generation of picosecond and femtosecond x-rays using subnanosecond laser pulses.

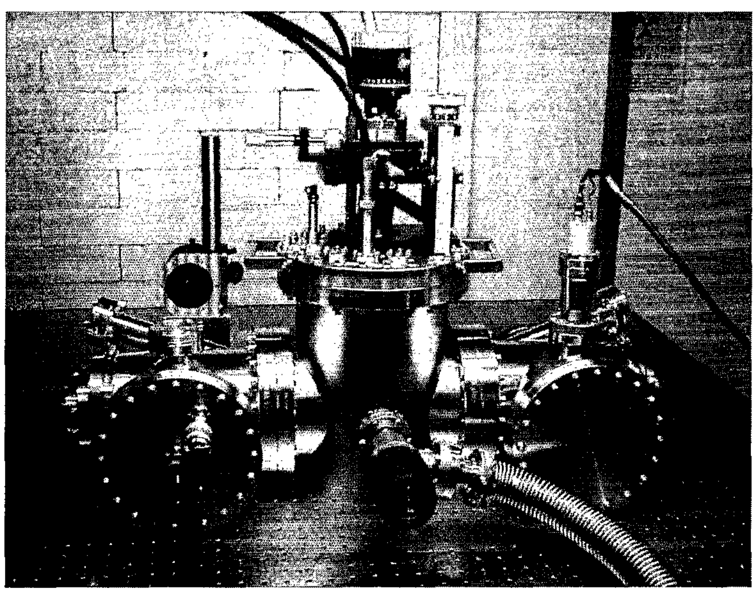


Figure 7: Picture of the interaction cell for Thomson-in-capillary experiment before installation into the electron beamline.

Table 1 shows demonstrated and expected parameters of the BNL Thomson source. With the improved laser and e-beam the dramatic increase of the x-ray intensity looks quite straightforward. The nonlinear effect will not allow achieving high spectral brightness in the free-space interaction. A plasma channel will serve for this purpose. Such performance will make the BNL source a unique tool for multidisciplinary ultra-fast x-ray studies.

Table 1. Recent results and future plans for the BNL Thomson source

PARAMETER	Present status	Design (free space)	Design (channel)
CO_2 LASER			
Pulse Duration [ps]	200	3	200
Pulse Energy [J]	6	6	6
Peak Power [GW]	30	2000	30
RMS Radius at Focus [μm]	32	32	32
Waist Length [mm]	4	4	4
ELECTRON BEAM			
Energy [MeV]	60	60	60
Bunch Duration FWHM [ps]	3.5	0.2	0.2
Bunch Charge [nC]	0.5	0.5	0.5
RMS Radius at Focus [μm]	32	32	32
X RAYS			
Peak Wavelength [Å]	1.8	1.8	1.8
Pulse Duration [ps]	3.5	0.2	0.2
Photons per Pulse	1.7×10^{8}	4×10^{9}	2×10^{9}
Photons per Second	5×10^{19}	2×10^{22}	10^{22}
Spectral bandwidth [%]	0.5	NA	0.5
Peak Brightness [photon/sec mm^{2}mrad^{2}0.1%]	5×10^{18}	NA	10^{21}

ACKNOWLEDGMENTS

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